CHAPTER 5 ANALYSIS METHODS

Analysis procedures and strategies are considered in this chapter, with emphasis on understanding the roles of the important input parameters and minimizing the amount of problem-specific data that must be entered. Where appropriate, differences from previous releases of RADTRAN are also discussed.

5.1 PACKAGE and SHIPMENT Values

5.1.1 Package and Conveyance Dimensions

Some package-related terminology, which might otherwise become confusing, requires clarification. The term “package dose rate” is **not** fully synonymous with the term “Transport Index” (TI). All RAM packages have a dose rate, but not all RAM packages have a TI. TI is a regulatory quantity that applies only to certain package types, as defined in regulations of the International Atomic Energy Agency, the U.S. Department of Transportation and the U.S. Nuclear Regulatory Commission (NRC) (49 CFR 173 and 10 CFR 71, respectively). In 10 CFR 71 and elsewhere, TI is defined as the **maximum** radiation level in millirem per hour at any point 1 meter from the external surface of a package. For exclusive-use shipments, however, the regulations abandon the TI concept. Instead, they regulate the dose rate at 2 m from the “vertical planes projected by the outer lateral surfaces” of the railcar or vehicle. ➨***Values for dose rate 1 m from the surfaces of package(s) and conveyance(s) must be entered in RADTRAN 5 regardless of which regulations govern the package(s) being analyzed.***

RADTRAN is designed to take advantage of the fact that this dose rate at 1 meter from the package surface is a **maximum** and either (1) is directly measured for regulatory compliance purposes or (2) can be calculated from a similar maximum measured at 2 meters. Real 3-dimensional packages, however, often have dose rates that are considerably **less** than the maximum at many other points on the package or conveyance surface (Figure 5-1A). For example, dose rates at 1 m from the surface of a DHLW (Defense High Level Waste) rail cask may vary by three orders of magnitude from 32.9 mrem/hr at cask midpoint to 0.02 mrem/hr at the corner (Wan & Scheringer, 1983). Spreads of one order of magnitude for gamma readings and two orders of magnitude for neutron readings were recorded at the cask surface on a TN-24 spent-fuel-storage cask with aged fuel contents (EPRI, 1987).

RADTRAN 5 does not account for the dose-rate variation described above. No generalized method of predicting field shape from package shape now exists, even for isotropically radiating materials, and few package contents are isotropically radiating. Many package contents display complex field-strength variations (e.g., spent fuel). In the absence of a general method, the approach taken in RADTRAN is necessarily geometrically simple and conservative. The package is modeled as an isotropically radiating sphere that emits the ***effective dose rate*** at a radius equal to {[(0.5)CPD] + 1}, where CPD is the ***Characteristic Package Dimension*** (Figure 5-1B). ➨***The CPD is an actual package dimension.*** For example, in cylindrical packages (e.g., most spent fuel casks), the characteristic package dimension is equal to length.[1] For a sphere, it is the diameter, and for a cubical package it is the longest internal diagonal.

[1] For analysis of a package or vehicle with a characteristic dimension greater than 4 m, the basic formula for calculating K_o significantly overestimates the actual dose rate, and RADTRAN 5 automatically makes an adjustment. For a package dimension greater than 4 m, the value for the actual characteristic package or vehicle dimension is replaced with a value for an effective package dimension, which is calculated by RADTRAN 5 according to the following equation:

$$D_{eff} = 2 \cdot (1 + 0.5\ D_{act})^{3/4} - 0.55$$

where D_{eff} = effective dimension and D_{act} = actual dimension.

The RAM-carrying vehicle is also assigned a characteristic dimension. The user enters values for characteristic dimensions (in meters) for each package and vehicle type. The code calculates a coefficient, K_o, from the CPD. K_o is often called the 'shape factor,' and it is used in subsequent dose calculations.[2] ➨***RADTRAN incident-free results are highly sensitive to the value of K_o, and the user should select values of dose rate and CPD with great care.***

Figure 5-1A *Example of Realistic Radiation Field Strength Isobar [-----] Around a Cylindrical Package with a CPD Equal to Length and a Maximum Dose Rate at 1 meter as indicated.*

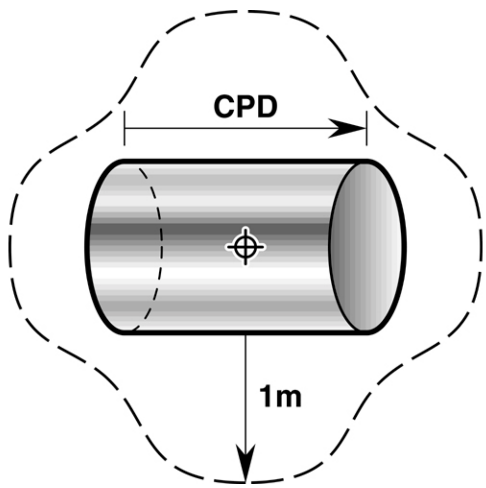
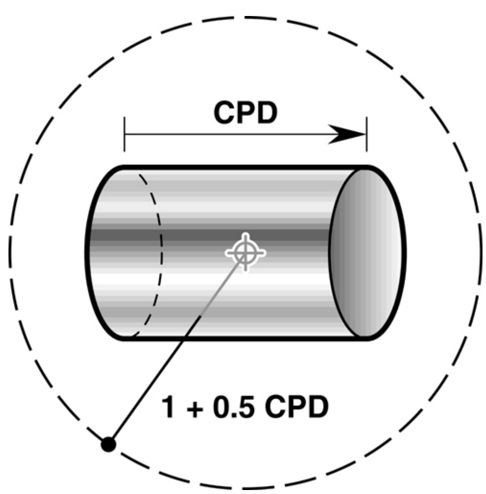


Figure 5-1B *Radiation Field is converted in RADTRAN 5 into a spherical, isotropically radiating field with its centerpoint at the geometric center of the package. The Field Strength at the radial distance of 0.5CPD + 1 is equal to the Maximum Dose Rate at 1 meter.*



The third type of CPD is "crew-view" CPD. It is the characteristic dimension of a package silhouette as viewed from the crew's vantage point. It is often markedly different from the silhouette of the same package for other exposure groups (e.g., handlers). For cubical packages

[2] For close-proximity exposure groups, a line-source model is used (Weiner & Neuhauser, 1992).

the “crew-view” is the diagonal across one side; for spherical packages, it is the diameter, just as for the regular CPD (Figure 5-2). The application of the crew-view CPD is discussed in Section 5.1.3.

As noted above, the entire shipment also is assigned a characteristic vehicle dimension (CVD). For example, the trailer of a tractor-trailer carrying a packed array of radiopharmaceutical packages may be treated as a single entity for the purpose of calculating external radiation doses. Finley et al, (1988) contains an example of this application.

Figure 5-2A
The Characteristic Package Dimension (CPD) of a Cylinder Is Length (meters)[●——●] Crew-View CPD is Diameter (meters) [◄►]

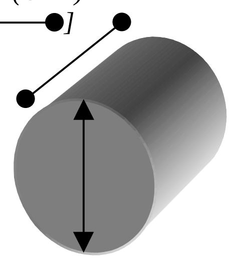


Figure 5-2B
CPD of a Cube is Longest Internal Diagonal (meters)
Crew-View CPD is Diagonal on a Side (meters)

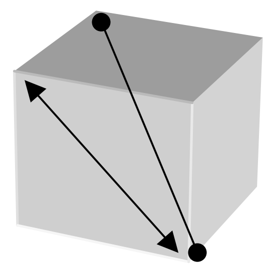
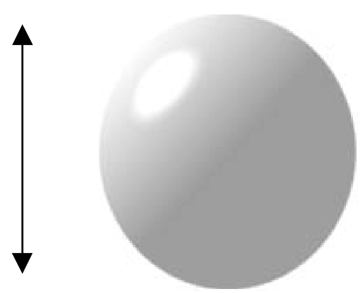


Figure 5-2C
CPD and Crew-View CPD of a Sphere are both equal to the diameter (meters)



5.1.2 Package and Shipment Dose Rates

Dose-rate values are among the most important data entered in a RADTRAN 5 input file. Recall that the maximum dose rate in mrem/hr at any point 1 m from a package or at 2 m from the vertical planes projected by the outer lateral surfaces of the transportation vehicle is regulated by law. Recall also that the maximum dose rate at 1 m is a RADTRAN 5 input value, which is used to estimate conservatively the field strength around the package or shipment.

The field-strength estimate for each ***package*** is used to calculate handler dose. The field-strength estimate around a vehicle (***shipment***) is used to calculate doses to persons beside the transport link (off-link), doses to persons sharing the transport link (on-link), and doses to persons at stops. The following guidance indicates the best ways of handling various package/shipment configurations.

Single-package shipments.

This is the simplest case. The shipment dose rate may be set equal to package dose rate, which normally is conservative. However, if the package is significantly narrower or shorter than the conveyance in which it is transported, then the actual shipment-level dose rate should be calculated or measured and used instead. The source-to-crew distance is usually the distance from the ***center*** of the package to the crew compartment. However, if a distinct crew-view dimension is used, then the same dose rate is used but the source-to-crew distance is measured from the ***end*** of the package closest to the crew compartment.

Multiple-package shipments.

- **Arrays**. This configuration usually applies to small packages. In most cases, numerous packages fill the space available for cargo or palletized groups of packages are evenly distributed within the space. The shipment dimension (CVD) represents the conveyance cargo space (usually trailer or railcar length). One should note that the estimate of dose rate at any given distance from a shipment increases non-linearly with increasing shipment dimension for a fixed shipment dose rate (DR_v). ➨***Use of a shipment dimension greater than approximately 10 m is not recommended.***

One still enters individual package dose rates as well as a shipment-level dose rate for the conveyance. ➨***The shipment dose rate is not equal to the sum of the package dose rates.*** It must be measured directly or calculated by hand because self-shielding usually makes the shipment dose rate significantly smaller than the sum of the individual package dose rates. An example of this approach may be found in Finley et al. (1988). Individual package dose rates also are required, however, because doses to handlers are always calculated on the package level.

- **Two or a few packages**. These are often special cases involving Type B packages. Individual cobalt-60 pins for commercial irradiators, for example, might be shipped in the following configuration: one per package; two packages at a time; truck mode. The vehicle-level dimension selected by the user to represent such a shipment depends on package placement within the cargo space. Type B and other heavy packages are generally evenly spaced to distribute the load. For example, in the case of two packages shipped in a single trailer, they could be tied down at the centerpoints of the two halves (measured from front to back) of the trailer bed. Total trailer length could be the CVD for this configuration; the maximum dose rate 1 meter from the trailer edge midpoint would have to be measured or calculated DR_v (Figure 5-3, Option 1). Alternatively, one could model the same example as two shipments each with a CVD equal to half the trailer length and with shipment dose rates measured at 1 m from the midpoint of each trailer half (see Option 2). For a 7x3-m trailer and packages 1-m in diameter, Option 1, with the larger vehicle dimension, yields a dose result that is about 40% higher than for Option 2. This occurs because of the non-linear nature of the k_0 and DR_v functions. As was noted above, this non-linearity tends to increasingly overestimate the dose-rate values as CVD increases. Therefore, Option 1 may be preferred for analyses where conservatism is desired, but Option 2 gives a better dose estimate.
- **Other configurations.** There are many possible arrangements of packages within a vehicle, and RADTRAN permits all variations to be characterized. Among special cases one might encounter are those in which the edge of the trailer or railcar is coincident with the edge of the package (e.g., TRUPACT shipments to the Waste Isolation Pilot Plant). If it is a single package, then the vehicle and package dose rates are equal. When a package occupies most or all of the cargo space available (e.g., many spent-fuel casks), then the package CPD is set equal to the CVD.

Figure 5-3A Option 1 - *Models Two or a Few Packages Widely Separated in the Same Conveyance - Model as Single Shipment with CPD Equal to Trailer or Railcar Length and Dose Rate Calculated at 1 m from midpoint of trailer or railcar.*

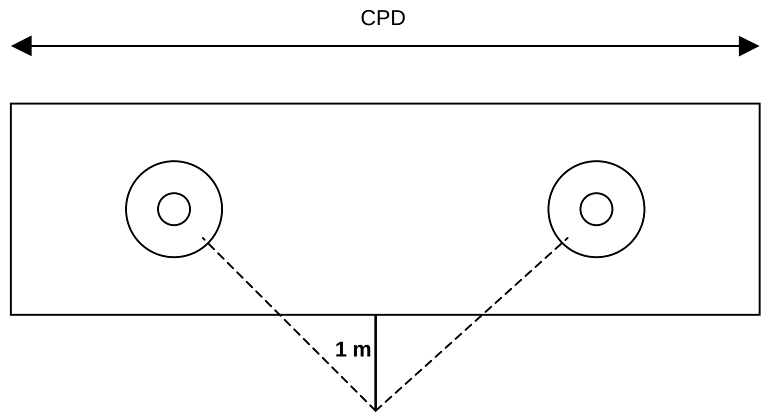
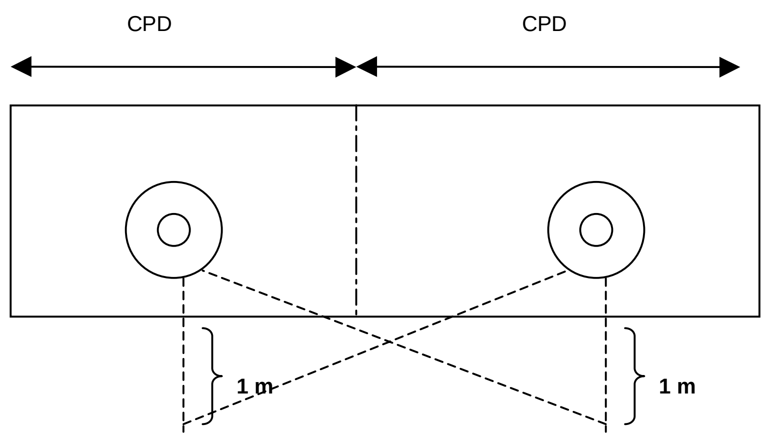


Figure 5-3B Option 2 – *Models Two or a Few Packages Widely Separated in the Same Conveyance – Model as Two or More Separate Shipments each with CPD Equal to a Fraction of Trailer or Railcar Length and Dose Rate at 1 m from Midpoint of each Fraction of Trailer or Railcar.*



5.1.3 Crew Shielding

➨**Crew shielding may be directly accounted for in RADTRAN 5 by means of the crew modification factor.** In previous releases of RADTRAN, crew shielding could only be accounted for indirectly, by artificially increasing the source-to-crew distance. With the crew modification factor, the user can easily account for shielding that may be installed in cabs of semi-tractors or ship's bulkheads, for example. Data that must be supplied by the user are:

- The "crew-view" dimension. Conveyances such as combination trucks often have "crew-view" dimensions that are smaller than those used to calculate doses for members of the public.
- The crew-to-source distance, which should be measured from the **closest edge** of the package or packed array to the center of the closest location for a crewmember (usually the crew cabin).

5.1.4 Gamma and Neutron Components of Dose Rate

Values for a neutron component of dose rate for fission neutrons are available for use in RADTRAN 5. The derivation of these values was originally given in the RADTRAN 4 Technical Manual (Neuhauser and Kanipe, 1989). To summarize briefly, they were obtained with neutron cross-section data from the ENDF/B-V (Magurno, 1983) cross-section data library generated with the NJOY code (MacFarlane, 1982). The source was assigned an energy spectrum obtained from Oak Ridge National Laboratory calculations of the neutron flux at the surface of a lead-shielded spent fuel shipping cask. The neutron transport calculations were performed with the ONEDANT code, which solves the one-dimensional, multigroup, Boltzmann transport equation by the discrete ordinates method (O'Dell, 1982). The ENDF library, NJOY system, and ONEDANT code are discussed and evaluated for use in transportation analysis by Parks et al. (1988).

To be compatible with the RADTRAN calculational strategy, the neutron rate as a function of distance is expressed in the following form

$$DR(x) = K\, e^{-\mu x} (1 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4)/x^2 \ ,$$

where

$DR(x)$	=	the dose rate as a function of x
x	=	distance in meters from the source
K	=	constant, and
μ	=	linear absorption coefficient for the surrounding medium (air).

The linear absorption coefficient for air (μ_{air}) was assigned a value of 7.42E-03 m^{-1} (Madsen et al., 1986; p. 43). Four unitless coefficients (a_1, a_2, a_3, and a_4) were then derived for fitting the shape of the dose rate-vs.-distance curve to the shape of the selected neutron transport curve in air at 50 percent relative humidity. These values are:

a_1 = 2.02E-02
a_2 = 6.17E-05
a_3 = 3.17E-08
a_4 = 0.0.

Although it is unlikely that another neutron transport curve might be appropriate, the user is allowed to enter new values for the coefficients into the input data file with keyword TRANSFER (see Chapter 3 for discussion of data entry). All four coefficients must be entered even if only one changes in value. Workstation/mainframe users enter them as the last four numbers in the five-number array under the second-level keyword NEUTRON and the first-level keyword TRANSFER (Table 3-2). The first number in this array is the linear absorption coefficient (μ), which also may be redefined by the user.

A similar treatment is possible for gamma radiation (second-level keyword GAMMA under TRANSFER), but the atmospheric effect (i.e., attenuation and buildup in air) is comparatively insignificant. Therefore, for gamma radiation the values of μ, a_1, a_2, a_3, and a_4 are set to zero in order to reduce the exponential term in the dose rate equation to unity. The equation for gamma thus reduces to the form used for a gamma point or line source in the RADTRAN calculational strategy, namely, $DR = K/x^2$ or $DR = K \times /x$ (Madsen et al., 1986, p. 13).

Separation of dose rate into neutron and gamma components is useful only for packages in which a significant fraction of the external dose rate is attributable to neutrons (e.g., aged spent fuel). A breakdown of the gamma and neutron components of dose rate at 1 meter for representative truck and rail casks and fuel ages of from 5 to 25 years is given in Parks, Hermann & Knight (1985). For most materials, the user should treat the external radiation field as consisting solely of gamma radiation. The user always has the option of performing external transport calculations and curve fitting to obtain new coefficients. An analysis of a multiple-package shipment containing dissimilar packages should *not* rely on extrapolation from package-by-package gamma-neutron breakdown, because of differential shielding and absorption by surrounding packages. The calculated or measured *shipment-level dose rate* may be split into gamma and neutron components, if necessary, that are derived from measurement or modeling of the shipment configuration.

5.2 Multiple-Radionuclide Materials

5.2.1 Assignment of Physical-Chemical Groups

Few radioactive materials consist of single radionuclides; most are mixtures. The physical and chemical properties of radionuclides and their compounds vary widely, and the behavior of radionuclides and their compounds in response to mechanical and thermal forces potentially encountered during accidents depends strongly on these properties. The first step toward accounting for them is to list all of the important radionuclides in the package(s) being analyzed under the PACKAGE keyword. ➨**The importance of an accurate radionuclide inventory cannot be underestimated.** When analyzing numerous small packages with variable contents, however, one may use statistical methods. Allow the code to automatically enter radionuclide-specific data directly from the internal isotope library whenever possible. Data entry is thereby simplified, and by reducing the amount of hand-entered data, the frequency of input errors is reduced. Complex materials containing up to 200 radionuclides can be modeled realistically. Methods are available, however, to reduce the number of nuclides considered without loss of accuracy, and these are discussed in Section 5.2.2.

The second step is to determine whether physically and chemically distinct groups of elements are represented in the material(s) being considered. Examples of chemically distinct groups are noble gases (e.g., krypton), volatiles (e.g., cesium in various forms), and transuranic oxides (e.g., plutonium oxide). An element may fall into more than one group in a material. An example of an isotope that may be in two distinct groups is cobalt-60 in pressurized water reactor (PWR) spent fuel. The isotope is an activation product and is found (1) in metallic fittings of fuel assemblies and (2) in crud on the surface of the fuel rods. The former is in a non-dispersable form that does not contribute to potential releases in severe accidents, but the latter may be spalled off of the fuel rods following impact. The resulting particulates may then be available for release. Since cobalt-60 produces a high-energy gamma, it is very important to model this element correctly. Only the cobalt-60 in crud should be modeled as available for release in analyses of PWR spent fuel.

For a given material, only elements with similar release behavior in **all** accident-severity categories should be grouped together. For example, ruthenium and cesium are volatile elements which will behave similarly in many thermal environments, but ruthenium may undergo chemical changes in a severe fire and an oxidizing environment that cesium does not. Therefore, these two chemical species should be assigned to two separate physical-chemical groups.

The designed-in flexibility of RADTRAN 5 allows each group to be treated separately. Since as many as 15 physically and chemically distinct groups of elements may be used in a single analysis, even the most complex materials can be modeled. An example of a complex material (spent fuel) is given in the sample input file in Chapter 3.

Each physical-chemical group must be assigned appropriate values for the release fractions (RFRAC), aerosol fractions (AERSOL), respirable aerosol fractions (RESP), and deposition velocity (DEPVEL). ➨***The Dispersability Categories used in earlier releases of RADTRAN are no longer used in RADTRAN 5***. However, the table of former default values for these categories remains a good guide to AERSOL and RESP values in the absence of any better information, and it is reproduced here from Neuhauser & Kanipe (1992).

Table 5-1. General Guide to AERSOL and RESP Values Suitable for All Severity Categories

Material Type	***Aerosol Fraction***	***Respirable Fraction***
Immobilized	1E-06	0.05
Loose Chunks	1E-02	0.05
Large Powder	1.5E-01	0.05
Small Powder or Nonvolatile Liquid	1E-01	0.05
Flammable	1E+00	1
Liquid	1E+00	1
Gas	1E+00	1
Undispersed (Loss-of-Shielding)	0	0

In summary, each radioactive element or compound is assigned to a group according to its physical and chemical properties. An element also may be assigned to more than one group if it appears in more than one physical-chemical form in the material being analyzed.

For shipments carrying packages with more than one type of contents, each package type must be separately characterized. The behavior of a multiple-package array in potential accident conditions is often different from the behavior of a single package, even if the packages are all identical. In an impact accident, for example, packages on the struck side of the vehicle generally will absorb more impact force than packages on the opposite side. Certain accident scenarios may involve what is referred to as inertial crush; when the force is translated from one package to the next in a manner such that package(s) distant from the impact point may be most affected. Packages also may act as thermal barriers in a fire accident, shielding other packages beyond them. Factors such as these must be considered and evaluated on a shipment-specific basis before assigning release fractions, etc.

5.2.2 Using a Relative Hazard Index to Reduce Large Radionuclide Inventories

If the number of radionuclides in a material is large, as in spent fuel, for example, then radionuclides that contribute less than a predetermined percentage to the overall hazard (e.g., 10, 1.0, or 0.1 percent) may be disregarded to simplify the analysis. The use of a relative hazard index for RAM transportation analyses was pioneered by Sandia National Laboratories. Various types of indices are discussed below.

Effective Dose Equivalent Factors
These factors give dose per unit intake for inhalation and ingestion for each radionuclide and are compiled and updated regularly by the DOE and the EPA (e.g., DOE, 1988a,b and EPA, 1993). When each is multiplied by the package inventory of the appropriate radionuclide, the resulting list represents the relative hazard of the material. For example, the data in DOE (1988b) was used to select those isotopes that contribute to 99.9% of the total health hazard in a recent DOE EIS dealing with research reactor spent fuel (DOE, 1995).

Maximum Permissible Concentrations (MPCs) and similar metrics
Atmospheric dispersion generally represents the primary, and often the only, means of dispersing radionuclides beyond the immediate vicinity of an accident site, even in extremely severe accidents and even for waterway modes. For this reason, values such as the International Commission on Radiological Protection (ICRP) Maximum Permissible Concentrations in Air (MPCs), Annual Limits on Intake (ALIs), and Derived Air Concentrations (DACs) are attractive candidates for use in developing a relative hazard index. All three are described in ICRP (1979) and ICRP (1990). For example, Maximum Permissible Concentrations in Air ($MPC_{air)}$ were used to develop a radiological hazard (RADHAZ) index for radionuclides present in 10-year-old PWR spent-fuel during analysis of repository alternatives (Wilmot et al., 1983). The authors used the following relationships:

$$\frac{\text{Inventory of isotope i (Ci)}}{MPC_{air}\text{ for isotope i}} = RADHAZ_i$$

and

$\sum RADHAZ_i$ over all isotopes in spent fuel = Total Radiological Hazard
(for inhalation pathway).

By retaining only those radionuclides that contribute, by summation on a rank-order basis, to 99.9% of the total radiological hazard (inhalation), Wilmot et al. reduced the size of the radionuclide list entered into RADTRAN to less than 10 without noticeably affecting the result. The radionuclides that were retained were cobalt-60, strontium-90, ruthenium-106, europium-155, cesium-134 and cesium-137, and several isotopes of plutonium.

Activity Limits
A similar method, based on Activity Limits (particularly A_2 values) can be used. The International Atomic Energy Agency (IAEA) defines A_2 as "the maximum activity of radioactive material, other than special form radioactive material, permitted in a Type A package" (IAEA, Safety Series 6, 1985). A Type A package meets the General Requirements for All Packagings and Packages, but is not accident-resistant, as are Type B packages.

This approach yields a nuclide list similar to that obtained with MPCs for the spent-fuel example above. With 5-year-old spent fuel, additional elements such as americium and curium are included in the list. None of these methods should be applied blindly, however. Krypton-85, for example, is generally included in the final isotope list for spent fuel (e.g., Wilmot et al., 1983; DOE, 1995). Although krypton-85 is inert and poses a relatively low hazard, it is present in spent fuel as a gas and much of the inventory would be released in the event of a severe accident, rather than remain trapped in the fuel and cask structures as many solids would. Thus, it is reasonable to include this radionuclide regardless of its hazard index. Similarly, radionuclides that are present in large amounts by mass, even thought their specific activities are low (e.g., uranium in spent fuel), or that are highly biologically active (e.g., tritium and iodine-131) should not be automatically excluded on the basis of a numerical hazard ranking alone.

In summary, the user may apply a relative hazard index to a multiple-nuclide material in order to simplify an analysis. However, special features such as gaseous state, mass fraction, and biological activity, should be considered when compiling a defensible final list.

Historical Methods

Two methods that were used to simplify computations when computers were less powerful and access to them more limited should be mentioned, although they are seldom, if ever, used today. The first was a weighted-average method, used to approximate the gamma source strength of spent fuel in NUREG-0170 for loss-of shielding accidents (NRC, 1977, Tables A-5 and A-6). Today, it is recommended that measured surface-dose-rate values be used.

Also in NUREG-0170, the entire inventory of volatile fission products in spent fuel was modeled as cesium-137, the single most hazardous radionuclide in this class (NRC, 1977, Table A-5). This historical method yields results that are too high. The practice is obsolete since it is now easy to realistically model the actual radionuclide inventories of spent fuels and most other complex materials.

5.3 Route Data

This section deals with analyses in which the routes being analyzed are defined by a set of route segments. Additional RADTRAN applications of route segments are discussed in Section 5.5.3.

5.3.1 Aggregate Route Segments and Other Data

An aggregate route segment is defined as the sum of all portions of a route that satisfy some predefined criterion. For purposes of analysis, it is treated as a single route segment. The resulting collective or aggregate route segment has all properties specified by the criterion except length. The length of the aggregate segment is equal to the sum of the portions as defined above.

➨***Route-segment aggregates, however defined, must be jointly inclusive and mutually exclusive.*** In other words, (a) the sum of the lengths of all the various route-segment aggregates must equal the total length of the route and (b) no individual segment of the route can be a member of more than one aggregation class defined by the criteria.

The most common aggregation criterion is population density. This criterion was used in NUREG-0170 (NRC, 1977), and has been used in numerous risk analyses since (e.g., Wilmot et al., 1983; DOE, 1995). Aggregated population-density data are readily obtained from the output of transportation routing codes such as HIGHWAY (Johnson et al., 1993) for truck mode and INTERLINE 5.0 (Johnson et al., 1992) for rail mode. Both of these codes, developed at Oak Ridge National Laboratory (ORNL), yield aggregate data for each node-to-node interval along the route. That is, all the rural segments between two major intersections are summed, as are the suburban and urban segments, respectively.

Stops may also be treated in an aggregate manner, especially when several similar stops may occur in the course of a single shipment. Madsen & Wilmot, 1983, provide this information for long-distance truck shipments. Similar data for rail operations in the Unites States was collated by Ostmeyer, 1986, from information found in Wooden, 1986. This is discussed at greater length in Section 5.3.4.

5.3.2 Linear Route-Specific Analysis

This section consists primarily of suggestions and useful information to assist the user in describing and analyzing route-related data. To perform linear route-specific analyses, a route is usually broken into

(a) links or segments, each of which represents a portion of the actual route,

(b) stops, each of which represents a stop along the route, and

(c) handlings, each of which represents a loading, unloading, or intermodal transfer event that occurs during the trip(s) being analyzed.

Up to 60 distinct route segments, 7 stops, and 8 handlings may be analyzed in a single computer run. If the number of route segments, stops, or handlings exceeds the maximum number per run for RADTRAN, then the user must perform multiple runs. The results of multiple runs may be collated in spreadsheets such as Microsoft Excel™ to yield total risk and consequence values for a complex problem.

Summation Check

➨***As noted above, the sum of the segment lengths should equal the total route length.*** Because there can be no internal check to ensure that this condition is satisfied, the user ***must*** perform this check. This check is most easily performed when data are entered in a spreadsheet, which is another reason why the use of spreadsheets is recommended for keeping tracking of the large amounts of data required by RADTRAN 5. The use of spreadsheets in building input files is discussed in Neuhauser et al. (1995)

Population Density

High-resolution sources of population data are available. The Bureau of the Census is the single best source of digitized data for the United States. Census data must be converted into population-density values suitable for use in RADTRAN. The population density within a predetermined bandwidth (usually 1600-m) of the highway or railroad must be determined for overland modes. Population densities under a plume footprint must also be determined if the user is applying the ISOPLETHP option. Methods for developing these population data with a GIS (Graphical Information System) have been developed at SNL (Mills, Neuhauser, & Kanipe, 1995). ORNL also has updated its previous routing codes (HIGHWAY and INTERLINE) with a GIS platform. The new code, called TRAGIS, will be publicly available in late 2000 (Johnson et al., 2000).

Accident Rate

The units for this variable are usually accidents per vehicle-kilometer. National accident-rate data are compiled and published annually by various groups in the U.S. Department of Transportation (USDOT) such as the National Transportation Safety Board (NTSB) and the Federal Rail Administration (FRA). Some of these data are available in electronic format (e.g., DOT, 1994). The relationship between accidents and railroad track class is discussed in McClure et al. (1988). The U.S. Coast Guard collects U.S. maritime accident data. Lloyd's of London maintains the Lloyd's Maritime Information Service accident reports, which are available for a fee.
Less comprehensive but locally more detailed data can sometimes be obtained from state and municipality highway or transportation departments (e.g., Smith, 1982).

In most cases, data collected in the United States are reported either in terms of accidents per one million vehicle-miles or in tabular form with two columns of data (total number of accidents and total millions of vehicle-miles traveled). The latter are often embedded in tables with various other data and must be extracted by the user. The data are not broken down into convenient rural, suburban, and urban categories. For example, the category labeled as URBAN by the USDOT usually is designated according to political boundaries (i.e., city limits) rather than actual population densities. Accident rates must be converted to metric units. Methods for developing rural, suburban, and urban rates are discussed in NRC (1977) and Wilmot (1983).

When analyzing carriage by a specific type of vehicle, an accident rate for that vehicle type should be used whenever available, rather than less vehicle-specific values. For example, nearly all Highway Route Controlled Quantity (HRCQ) shipments of radioactive materials by highway mode are carried by combination trucks (tractor-trailers), and USDOT data are available for this truck type. The latter should be used in preference, for example, to data from the All Vehicles category. The data source and category should always be stated in the documentation of an analysis.

Most data sources, whether they explicitly state so or not, include only reportable accidents (i.e., those that exceed some dollar value in damages or those that involved a fatality). Correcting for underreporting only serves to raise the fraction of accidents of low severity (and hence to lower the fraction of high-severity accidents) and so is usually neglected. Accident-rate data for more than one year may be averaged, if desired, and the use of multiple years of data is recommended.

➨The accident-rate parameter is sometimes written less than rigorously as accidents/kilometer, but this should ***never*** be interpreted to mean an accident count per kilometer of roadway or railroad. The number of accidents that have occurred in a given route segment, if left unadjusted for usage of that route segment, is an improper (and useless) value. The denominator should always be taken as referring to vehicle-kilometers unless explicitly stated otherwise.

For air and maritime modes, accidents *per voyage* or accidents *per air transit* are often the forms in which data are presented. They can be converted to accidents/vehicle-kilometer if nautical-mile or air-mile distance values, or average trip distances, or some similar parameter can also be obtained. If they are used without modification, comment lines should be added to any analysis that uses an alternative form of accident-rate data to make sure improper comparisons are not made with other risks calculated on a per vehicle-kilometer basis.

Vehicle Density and Vehicle Occupancy
The DOT sources cited above also supply data on vehicle density for highway mode travel. For most analyses performed at Sandia, average vehicle occupancy is conservatively set to 2, although it is usually closer to 1 (e.g., DOT, 1994).

Segment Character Designation
Although segment-specific population densities must be entered, the user is asked, in addition, to indicate whether each segment is rural, suburban, or urban in *character*. The user enters R, S, or U to indicate rural, suburban, or urban character, respectively. Character designation controls the selection of accident-severity fractions, controls whether an ingestion-dose calculation is performed, and determines the selection of building-shielding factors [RR, RS, and RU (see Keyword Master List, Chapter 3)].

If the segment character designation is R, then the ingestion pathway is included, but if a segment is designated as S or U, ingestion is not calculated. However, the ingestion code (COMIDA) also gives a calculation for a so-called "maximum man," who is essentially a subsistence farmer (Abbott and Rood, 1994a,b). This dose value is always included in the RADTRAN output. It will bound any doses potentially incurred by a suburban resident with a backyard tomato plot, for example, in the unlikely event that the individual continues to grow and eat tomatoes subsequent to a contamination event.

In addition, if a segment is designated U, then expected values of total inhalation dose are modified to account for its two main components:
1. dose for persons indoors, and
2. dose for persons out of doors.

To obtain the first value, the baseline total inhalation dose is calculated on the basis of a uniform population density; then that dose is multiplied by the product of Urban Building Fraction (UBF) and Building Dose Factor (BDF). The UBF accounts for the fraction of persons indoors (or the amount of land surface occupied by buildings rather than streets, sidewalks, parking lots, parks, etc.), and the BDF accounts for the partial removal of particulates by building ventilation systems (Finley et al., 1980). The UBF has a STANDARD value of 0.9; the BDF has a STANDARD value of 0.05 (Englemann, 1990). The BDF factor used in RADTRAN 4 (8.6E-03; from Finley, 1980) is now considered too small. Both the UBF and BDF may be altered, of course.

The second term, which accounts for inhalation dose to persons outside of buildings (e.g., pedestrians, shoppers, and commuters), is calculated separately. In this term, the base dose value is multiplied by the product of Urban Sidewalk Fraction (USWF) and Ratio of Pedestrian Density to residential population density (RPD). The STANDARD values for USWF and RPD are 0.1 and 6.0, respectively (Finley et al., 1980). The RPD allows the user to account for non-residents, and all of them are modeled as being out of doors. The sum of the two terms is the adjusted collective inhalation dose.

Link Type

Link type is used to distinguish between various roadway types for highway modes only (truck, commercial van, and passenger van). If the user sets the link type to 1, then the route segment is modeled as a limited-access divided highway (i.e., an Interstate highway or other highway built to similar engineering standards). If the link type is set to 2, then the combination of zone designation and link type determines how the roadway is modeled. If the link type is set to 2 and the zone is designated either R or S, then the roadway is modeled as a non-limited-access, non-divided highway (e.g., an U.S. highway). If the link type is set to 2 and the segment is designated as U in character, then the roadway in that segment is modeled as a city street. For all other modes, the link type is set to 3.

This scheme is diagrammed below.
Link Type 1 ⇛ Limited-Access Divided Highway; Any Population Density
Link Type 2 ⇛ Zone R or S ➻ U.S. Highway (non-limited-access, non-divided)
Zone U ➻ City Street
Link Type 3 ⇛ Any Non-Highway Mode

This flexibility is important even for highway-route controlled quantity (HRCQ) shipments such as spent fuel, which are required by DOT routing regulations to use Interstate highways. Access routes to and from the Interstates and state-designated alternate routes, which often must be evaluated in environmental documents, can be analyzed readily by use of the link-type settings. Differences in accident rates, population densities, traffic densities and other factors that may change according to road type, must be accounted for if the analysis is to be meaningful. In a recent example, an Interstate route from Florida to Washington State was compared with a route that avoided urban areas by traveling on U.S. Highways (Mills & Neuhauser, 1998a).

Fraction of Land under Cultivation

The user may enter values from 0.0 to 1.0 for this parameter only if the link is identified as R (rural in character; see Link Type above). If a link is identified as S or U (suburban or urban), then the RADDOG input file generator code automatically enters a zero for this parameter. If the user is manually creating an input file, then he or she must enter a zero value for all non-rural segments. The variable is used in the ingestion-dose calculation and accounts for the fraction of area in agricultural production, as opposed to the area occupied by roads, driveways, dwellings, barns, commercial buildings, parking lots, parks, forests, etc. No account is taken of seasonal differences. There is no STANDARD value for this parameter. Maximum values for this parameter are available from publications of the U.S. Bureau of the Census, but only for counties, a relatively low level of resolution.

If one wishes to "force" calculation of an ingestion dose for a link that is actually suburban or urban in character, then the user can designate the link as rural and enter a value for the fraction of land under cultivation. The latter value should be at least a factor of 4 or 5 smaller than the rural value. For example, the *County and City Data Book* (USBC, 1988) lists St Louis County, Missouri, which includes the City of St. Louis, as having 42,000 acres in cropland. The total area of the county is 506 square miles and the average population density was 1962 persons per square mile in 1988. At that time the fraction of land under cultivation in this highly urban county was approximately 0.13 (13%). Nearby Atchison County, Missouri, on the other hand, which is predominately rural (population density was 14.6 persons per square mile) had a fraction of land under cultivation of 0.77 (77%) in the same year. That is over five times the value for St. Louis County.

Population under Plume
Accidents may occur that result in airborne dispersion of RAM package contents. These accidents are characterized with the user entries for accident rate, severity fraction, release fraction, aerosol fraction, respirable fraction, and meteorological conditions. As in previous releases of RADTRAN, the area under the dispersion plume, the so-called plume “footprint” can be modeled as having the same population density as the bandwidth around the transportation corridor. This is normally acceptable for probabilistic analysis purposes. The population density in this bandwidth (usually 1600 m wide) is the basis for designation as rural, suburban or urban; off-link populations for incident-free dose calculations are located within the bandwidth. However, this modeling assumption leads to excessively large overestimates of downwind population for urban route segments. It is possible, but less likely, that a plume originating in a rural or suburban route segment would encounter higher density areas shortly beyond the bandwidth boundary. In order to better characterize such specific situations, an individual population density for each downwind isopleth may now be entered under the ISOPLETHP keyword. The Bureau of the Census is the best source of digitized information on population distribution in the United States. The population data must be used in conjunction with a GIS system to obtain useful plume footprint values.

5.3.3 Non-Linear Applications

In the so-called non-linear applications of RADTRAN 5, the links do **not** represent a sequential or aggregated set of route segments that define a route. This freedom to define route segments in nontraditional ways that has been built into RADTRAN 5 is extremely useful. The user can analyze and compare the same route or route segment(s) in a variety of conditions. Examples of applications include:

- comparisons of daytime and nighttime population densities (e.g., Mills and Neuhauser, 1998b);
- comparisons of rush-hour and non-rush-hour traffic conditions;
- comparisons of current and projected population densities (e.g., Neuhauser and Weiner, 1992a)
- doses in enclosed spaces such as airplanes from leaking radioactive material package(s) (Neuhauser, 1992).

This powerful analytical tool is limited in usefulness only by the quality and quantity of data available to the user.

5.3.4 Stop Data

To review from Chapter 3, for each stop (or an aggregate of similar stops), the user assigns values to the following stop parameters:

- alphanumeric identifier, up to 10 characters;
- vehicle identifier (previously defined under keyword VEHICLE);
- population density (persons/km^2) <u>**OR**</u> number of persons (#);
- minimum radius of annular area (m);

- maximum radius of annular area (m);
- shield fraction;
- stop time (hr).

There are two alternative methods for estimating the size of the potentially exposed population. In the first method, the minimum and maximum radii are set equal to each other; this is interpreted by the code to mean that dose will be calculated at an *average radial distance* from the shipment. In this option, the third value in the array is interpreted to mean *number of persons present at the stop.* These persons are modeled as if they were located at the specified average radial distance from the shipment(s) for the duration of the stop. In the second method, the maximum and minimum radii are not equal. This is interpreted by the code to mean that it should compute the area of an annulus (with the vehicle at its center) that has an inner radius equal to the smaller of the two radius values and an outer radius equal to the larger of the two values. The third value in the array is then taken to be a *population density*, which is used to calculate the number of persons within the annulus (the product of the population density and the calculated annular area).

➨***The user must be careful not to get the two stop options confused***. For example, entering a population-density value, rather than a count, along with an average distance (i.e., making the two radial distances equal), would mean the density would be interpreted as a specific number of persons located at that average distance. The result would usually be considerably in error. Studies that provide information on the values of these parameters for highway mode include Madsen & Wilmot (1983) and Griego et al. (1996).

If more than one stop is expected (e.g., cross-country truck shipment) and if exact stop locations cannot be known in advance, then the total expected stop time may be allocated to a single "aggregate" stop with average parameter values. For materials shipped by common carrier, this is often the only workable method. For truck shipments the aggregated stop time has been conservatively estimated to be equal to 0.011 hours per kilometer of travel (Madsen & Wilmot, 1983). This value includes rest stops, meal stops, and overnight stops on long trips. The use of aggregate stops for highway mode is common because one can expect truck stop locations to be restricted or pre-designated only when one is analyzing heavily controlled or monitored shipments. Most train stops are in railyards, and several reports have examined the potential for rail worker dose (Wooden, 1986; Ostmeyer, 1986; and ORNL, 1990). In the case of carriage by vessel, port-call stops are usually known well in advance and may last 24 hours or longer (Neuhauser & Weiner, 1992b).

➨Use Stop Model for LOS Analyses with Robust or Special-Form Materials

The LOS model in RADTRAN 5 is suitable for use with many RAM shipments such as radiopharmaceuticals, which are typically shipped in small amounts in non-accident-resistant Type A packages. For shipments of these materials, moderate to severe accidents can be expected to result in complete loss of contents of all affected packages. The LOS model in RADTRAN 5 is intended for such situations. The contents are presumed to be lying on the ground or on some vehicle surface in a manner that permits little self-shielding. Thus, the entire radionuclide inventory is multiplied by a gamma photon energy or neutron emission factor, as appropriate, to calculate a source strength. However, this approach is inappropriate for special-form materials and other robust materials such as spent fuel that can be expected largely to retain their structural integrity even in extremely severe accidents. In the latter case, the annular-area option of the stop model should be used to estimate LOS doses. The source strength should be estimated from the product of the surface dose rate of the material and whatever shielding factor is appropriate to account for only partial degradation of the packaging. The latter calculation will require a separate run of the code.

5.3.5 Handling Data

To review the discussion in Chapter 3, for each handling, the user assigns values to the following parameters following the keyword HANDLING:

- alphanumeric identifier, up to 10 characters;
- vehicle identifier (previously defined under keyword VEHICLE);
- number of handlers;
- average source-to-handler distance (m);
- handling time per package (hr/package).

The values of the last three parameters listed are a function of package size. Large containerized packages that are handled by spreader crane require several handlers. To move such a package from a truck to a ship's hold, for example, requires a crane operator, a spotter, and four or more additional workers (Neuhauser & Weiner, 1992b; Weiner & Neuhauser, 1992a). The package is modeled as a line source or a point source depending on distance. The average source-to-handler distance may be only a few meters, in which case a line source model is used. For packages that are smaller than a spent fuel cask but still large enough to require movement by forklift or similar equipment, the average source-to-handler distance decreases but so does the number of handlers. Finally, small packages that can be picked up and moved by hand (e.g., many radiopharmaceuticals) are analyzed in RADTRAN 5 by use of an empirical factor that relates handling time per package, source-to-handler distance, and other factors (keyword SMALLPKG; see Section 3.6).

➨Use HANDLING or STOPS to Model Inspector Dose

Highly regulated shipments (e.g., spent fuel) are often subjected to redundant radiological and mechanical inspections by various government entities, carrier representatives, shippers of record, etc. Each inspection adds an increment of inspector dose. Inspectors generally must be close to the package/conveyance being inspected; their exposure may be modeled by use of the HANDLING or STOPS subroutine. Suggested parameter values are discussed in Ostmeyer (1986) for rail mode and Weiner & Neuhauser (1992a,b) for ship and highway modes.

5.3.6 Evacuation Time

The time (in hours) that is required to evacuate a nearby population from the vicinity of an accident location is entered under the keyword EVACUATION.[3] The time is composed of (a) response time (i.e., the time it takes responders to reach the accident site, assess the hazard and initiate evacuation), and (b) actual evacuation time. The STANDARD value is 24 h. Evidence exists, however, to support use of a considerably lower value. A distribution of actual evacuation times from actual hazardous materials accidents is given in Mills, Neuhauser, & Smith (1995), and the mode (the "mean" of a log-normal distribution) is approximately 1 hour. Using Latin Hypercube Sampling (LHS) methods (Iman & Shortencarier, 1984) to sample from this distribution or a similar one developed by the user is the best way to deal with the uncertainty in this parameter (see Mills, Neuhauser & Kanipe (1995) for applications of LHS to RADTRAN).

5.4 Post-Accident Options

RADTRAN 5 contains decision logic that is based on calculated ground deposition and user-defined action thresholds. There are three possible courses of action:

- [3] The term "evacuation" in RADTRAN refers collectively to activities separately labeled as "evacuation" and "relocation" in the MACCS code used by the NRC for fixed site analysis.

- If the ground deposition (Ci/m^3) exceeds the minimum clean-up level (keyword CULVL, Section 3.6), then the area under the plume is modeled as being evacuated at the end of the time entered under keyword EVACUATION (see Section 4.4);
- If the ratio of ground deposition to clean-up level exceeds the maximum threshold (keyword INTERDICT), then the area is modeled as being permanently interdicted. That is, no residents return to the area and no additional dose is accumulated by these residents beyond what was already received in the hours prior to evacuation;
- If the first but not the second threshold value is exceeded, then the area is modeled as being cleaned-up to acceptable levels, after which returning population are modeled as being chronically exposed to residual material at the action-threshold level.

As noted previously, the STANDARD value of the time required for surveying potentially contaminated areas (keyword SURVEY) is 10 days, which is less, probably considerably less, than such an activity would be expected to take in reality (Chanin & Murfin, 1996). However, in view of the uncertainty in estimating this parameter value, the short 10-day value has been used because it is *radiologically conservative*; that is, it minimizes time for radioactive decay and thereby maximizes exposure from any short-lived isotopes at all subsequent times. The time required for clean-up is not explicitly accounted for, but actual clean-up times are most likely to be years or even decades (Chanin & Murfin, 1996). Because it is assumed that cleanup would always result in subsequent exposure of returning population to contamination at the minimum action-threshold level, however, actual clean-up time does not greatly influence the population-dose calculation.

5.5 Output Options

There are two output formats: dose and health-effect. Both types of output are usually desired for an analysis. ➨***Radiological risks should always be presented at a minimum in the dose format (expected population dose-risk) since it is the least derivative of the two values.*** Expected health effects (e.g., latent cancer fatalities) may be obtained by a second run of the code or by calculations external to the code. In both output options, early radiological fatality and nonradiological fatality calculations are always performed.

5.5.1 Output as Dose-Risks or Health-Effects Risks

The population-dose output format is selected on the FORM menu screen. Workstation users should enter the keyword UNIT on the FORM line. Doses are calculated for the exposure pathways shown in the box. Three of the dispersion-pathways results are what are called "prompt" doses. That is, doses that occur during or within a few hours of cloud passage. They are cloudshine, inhalation, and groundshine during evacuation. For each isotope in a material, effective dose equivalents for inhalation, cloudshine, and ingestion are taken from the radionuclide library. Groundshine and LOS doses are calculated from isotope-specific photon-energy data (except for LOS doses for special-form materials, see Section 5.3.4). The resuspension pathway is merely a delayed, chronic inhalation pathway, corrected when necessary for clean-up, weathering, and radioactive decay.

Box 5-1
RADTRAN 5 Exposure Pathways

Direct Exposure to Package
Loss of Shielding (LOS)
And
5 Dispersion Pathways:
Cloudshine
Inhalation
Groundshine
Resuspension
Ingestion (societal)

The health-effects output format may be selected by either selecting it on the FORM menu screen or entering the keyword NONUNIT. If NONUNIT is selected, then STANDARD values of health-effects multipliers may be used for latent-cancer fatalities and hereditary disorders, or the user may supply others. As noted in Chapter 4, health-effects risks are given for each route segment and for each exposure pathway. Tables give the risks related to loss-of-shielding exposures, all dispersion-related exposures except ingestion, and societal ingestion. The conversion factors, e.g. LCF per person-rem, are listed in the tabulations of input data. ➨***If the stop model is used to perform an LOS analysis, then the user must estimate early effects (morbidities and mortalities) externally.***

5.5.2 Early Effects

Early or non-stochastic health effects only occur at high radiation doses. Their severity increases with increasing dose, and a threshold exists below which no effect is observed. They also may be called acute, deterministic, or prompt effects. Persons in close proximity to intense gamma and/or neutron sources during a loss-of-shielding accident could receive acute doses above the effects' thresholds; as could persons in the innermost isopleths who are exposed via the inhalation or groundshine pathways following a dispersal accident. Symptoms may appear within a few hours or days following exposure. Depending on dose, effects exhibit a range of severity from short-term anorexia or vomiting, hair loss, and erythema (skin reddening), which are accounted for in the morbidity estimates, up to and including mortality, which is accounted for separately.

Mortality
Mortality may be observed in a fraction of a population exposed to high doses delivered over short periods of time. Death may occur in days, weeks or months, depending on the magnitude of the dose, post-exposure medical treatment, and initial health status of the affected individual(s). The likelihood of mortality decreases if the dose is fractionated or protracted (ICRP, 1984). The 1-year dose is calculated and used to estimate mortalities in RADTRAN 5. The probability of death for a given acute bone marrow or lung dose is listed in an internal data table in RADTRAN 5 (see Table 5-2). This table is used to estimate mortality associated with doses calculated in an analysis. The data are derived from Evans et al. (1985) and are consistent with those used in the MACCS2 code. A mortality estimate is performed and printed regardless of the output option selected.

Morbidity
Morbidities or non-lethal clinical effects are also estimated in RADTRAN 5. As in previous releases of RADTRAN, several organ-specific effects are evaluated for the inhalation pathway. The organs included are:

- Lung
- Upper Gastrointestinal Tract (stomach)
- Bone Marrow
- Thyroid (radioiodine only)

The bone marrow and upper GI tract (stomach) are relatively radiosensitive, and the morbidity thresholds are lowest for these two organs. Lung tissue is among the most radiation resistant, and it has the highest morbidity threshold. Thyroid morbidity (noncancerous nodules and hypothyroidism) results almost exclusively from intake of radioiodine.

Table 5-1 – Mortality – Dose Relationship for Marrow and Lung Exposure

Marrow Dose (rem)	Fatality Incidence	Marrow Dose (rem)	Fatality Incidence	Lung Dose (rem)	Fatality Incidence
<160	0.00000	570	0.99482	<500	0.00000
160	0.00913	580	0.99679	525	0.00759
170	0.01234	590	0.99808	550	0.01050
180	0.01639	600	0.99889	575	0.01430
190	0.02143	610	0.99938	600	0.01922
200	0.02761	620	0.99967	625	0.02549
210	0.03510	630	0.99983	650	0.03341
220	0.04408	640	0.99992	675	0.04329
230	0.05475	650	0.99996	700	0.05548
240	0.06729	660	0.99998	725	0.07038
250	0.08188	670	0.99999	750	0.08837
260	0.09872	>670	1.00000	775	0.10988
270	0.11797			800	0.13529
280	0.13977			825	0.16498
290	0.16425			850	0.19925
300	0.19150			875	0.23830
310	0.22155			900	0.28218
320	0.25438			925	0.33077
330	0.28990			950	0.38372
340	0.32798			975	0.44042
350	0.36838			1000	0.50000
360	0.41078			1025	0.56130
370	0.45481			1050	0.62293
380	0.50000			1075	0.68335
390	0.54583			1100	0.74095
400	0.59172			1125	0.79420
410	0.63706			1150	0.84178
420	0.68123			1175	0.88274
430	0.72363			1200	0.91656
440	0.76371			1225	0.94326
450	0.80096			1250	0.96331
460	0.83499			1275	0.97755
470	0.86552			1300	0.98709
480	0.89237			1325	0.99306
490	0.91551			1350	0.99653
500	0.93502			1375	0.99840
510	0.95111			1400	0.99933
520	0.96406			1425	0.99974
530	0.97423			1450	0.99991
540	0.98199			1475	0.99997
550	0.98776			1500	0.99999
560	0.99192			>1500	1.00000

5.5.3 Unit-Risk Factors

The Unit-Risk Factor Method was developed in the early 1980s by Sandia National Laboratories, which also performed the first analyses in which this method was used (Wilmot et al., 1983; Neuhauser et al., 1984; Cashwell et al., 1986). Other analyses in which it has been used include DOE (1995). The method remains suitable for certain applications, such as comparisons of alternative packagings and content loading.

A unit-risk factor is defined as a quantitative risk (e.g., dose-risk, fatality-risk) associated either with transportation of a given shipment for a unit distance of travel, usually 1 km, or with a unit activity, e.g. one handling. The approach is useful when the user wishes to evaluate a large number of alternatives that differ from each other in only one or a very few package-related or route-related features.

To develop route-level unit-risk factors, reasonably consistent *route subclasses* must be identified. A route subclass can be defined as an aggregate of all portions of a route that have some property or combination of properties in common. The term "property" means a route-related RADTRAN variable (e.g., population density between a specified range, traffic count within a specified range, etc.). The most common route subclasses are based on population density (rural, suburban, and urban) [see Section 4.4.1]. A maximum of 60 subclasses per run may be defined by the user.

Unit-risk factors (URFs) are calculated for each route subclass with input data that are held constant for all other parameters including mode and shipment type. The number of shipments should be set to unity. The result should be a set of unit-risk factors expressing dose-risk (or, less desirably, health risk) per unit of travel for a single shipment in each route subclass for:

1. incident-free dose to transportation workers,
2. incident-free dose to the public,
3. accident risk,
4. non-radiological fatality risk from ordinary accidents.

They can be combined in an external calculation to express a unit shipment risk. URFs are shipment specific, and must be recalculated for each shipment variation such as radionuclide inventory or package type even if all other characteristics of the proposed transportation are the same.

The user can analyze a route by this method without having to go through the expensive process of gathering detailed data on individual routes. However, the unit-risk-factor technique cannot achieve a high level of resolution and is best suited for Programmatic Environmental Impacts Statements and similar types of high-level or generic studies. ➨**Great care must be taken to apply the URF technique appropriately.** For example, if a given material may be shipped by one mode in two distinct types of packagings with differing capacities, then the URFs for the low-capacity package are likely to be the smallest. However, an increased number of shipments would be required to transport the same amount of material to the same destination with the low-capacity packaging. Therefore, the *total* or campaign-level risk [Σ (URF_r x km_r, where r = route subsets 1 through r) x Number of Shipments] associated with use of the low capacity packaging could easily exceed that associated with use of the high-capacity packaging. The total risk comparison must be performed external to RADTRAN. If the comparison were omitted or the risks improperly calculated, then one might incorrectly conclude that the small package presented the lowest risk alternative. ➨**External calculations are not covered by RADTRAN software QA, and it is incumbent on the user to demonstrate their correctness**. One should also note that it is illogical and improper to calculate a unit-risk factor below the single-shipment level (e.g., for a single radionuclide in a shipment).

Radiological unit-risk factors could not be used in the absence of a linear-no-threshold (LNT) hypothesis. The LNT hypothesis for health effects of radiation exposure is currently being reexamined by various national and international bodies. Should it cease to be the preferred hypothesis, URFs could no longer be used, at least in their present form, to assess radiological impacts of RAM transportation.

Unit-risk factors for nonradiological fatalities do not suffer from a similar dependency on a linear hypothesis, with the exception of the so-called incident-free factor, which was intended to account for health effects of inhalation of diesel exhaust. The factor values were originally assigned on the basis of a rather generic assessment by Rao et al. (1981) in which an LNT relationship was assumed.[4] Beginning at about the same time, the effects of many components of diesel exhaust (e.g., benzene) had begun to be better characterized (Wark and Warner, 1981). Exposure thresholds have now been identified for most of these components (e.g., 10ppm for benzene; see Calabrese and Kenyon, 1991). In view of these developments, the use of an incident-free risk factor for nonradiological fatalities based on an LNT hypothesis can no longer be justified. ➨**Therefore, no STANDARD value has been recommended for the incident-free risk factor for nonradiological fatalities in RADTRAN 5, and the variable may be removed in a future release of the code.**

- [4] Values were assigned for urban areas only and were 1.0E-07 fatalities/vehicle-km for highway, 1.3E-07 fatalities/vehicle-km for commercial rail, and 6.5E-07 fatalities/vehicle-km for dedicated rail.